Certification Issues Relating to ABDR

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ABSTRACT

New tactical air vehicles are normally designed to be ballistically survivable on the modern battlefield by incorporating active and passive signature reduction and ballistic damage tolerance features. A large percentage of these air vehicles return from combat missions with various levels of combat damage or may suffer from ballistic threads while on ground. Maximum air vehicle fleet availability is essential during surge operations; therefore, quick assessment and repair of the damage are necessary.

Since certification of the platform as a system is covered for peacetime operations, qualified methods for assessment of damage and repair of structures / components together with tools and additional training for repair crews are required to achieve adequate risk / safety levels during combat operations

1.0 INTRODUCTION

The constant demand for improved performance in the development of new fighter / transport aircraft required reduced structural weight limits and has led to new design techniques, among them increased utilization of advanced fibre reinforced materials or advanced metal alloys with higher material allowables for the load carrying structures.

Although the trend for composites in structural applications in percent of structural weight will show an asymtotic amount of approx. 30% in future, (Fig. 1.0-1), the wetted area will be made almost exclusively from thermoset composites like CFRP, which is used in most cases as a combination of a high strength/modulus carbon fibre and a hot curing thermoset resin. A high percentage of modern fighter aircraft's exterior surface is covered with composite skins (Fig. 1.0-2), including fuselage, wings, horizontal and vertical stabilizer (e.g. for the Eurofighter about 70%). All of this graphite epoxy skin surface is load carrying, most of it primary structure.

Metal designs also increased not only in individual part size, but also in the integration of structural elements, i.e. machined stiffened skins or bulkheads

With the structural requirement of high mechanical loads for the primary load pathes in combination with local load introductions and stability criteria, the result is very often either thin-walled stiffened skin design and/or sandwich structures. The large amount of integrated structural elements with reduced number of fasteners dictate the requirement for maintainability and repairability of these elements, especially under the consideration of part costs and assembly effort.

Maintainability aspects are partly covered due to the damage tolerant design approach, in general today's composite structures are designed using a "Limited Fibre Strain Approach" at ultimate design loadcases, where the reduced material allowables account for a low energy impact damage level, ,that can be sustained without compromising structural strength over the entire life of the aircraft. For metal parts the

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14. ABSTRACT

New tactical air vehicles are normally designed to be ballistically survivable on the modern battlefield by incorporating active and passive signature reduction and ballistic damage tolerance features. A large percentage of these air vehicles return from combat missions with various levels of combat damage or may suffer from ballistic threads while on ground. Maximum air vehicle fleet availability is essential during surge operations; therefore, quick assessment and repair of the damage are necessary. Since certification of the platform as a system is covered for peacetime operations, qualified methods for assessment of damage and repair of structures / components together with tools and additional training for repair crews are required to achieve adequate risk / safety levels during combat operations

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working stress levels are chosen to accommodate safe fatigue lifes at stress riser locations, covering to some extent also possible local repairs due to maintenance / operational damage during service

However, damages exceeding these limits should not lead to the need of immediate replacement of parts or extensive A/C-downtime for disassembly, autoclave repair, reinstallation and inspection. The alternative of designing most components as fully exchangeable between A/C's is also limited, therefore the "Repair on Aircraft" capability for the structure becomes an important part of the maintenance concept for highly integrated structures, that need to be considered during design and qualification phases.

Some of this inherent tolerance to damage can also be utilized for ABDR purpose, given that the individual damage state is substantiated and the remaining capability can be qualified.

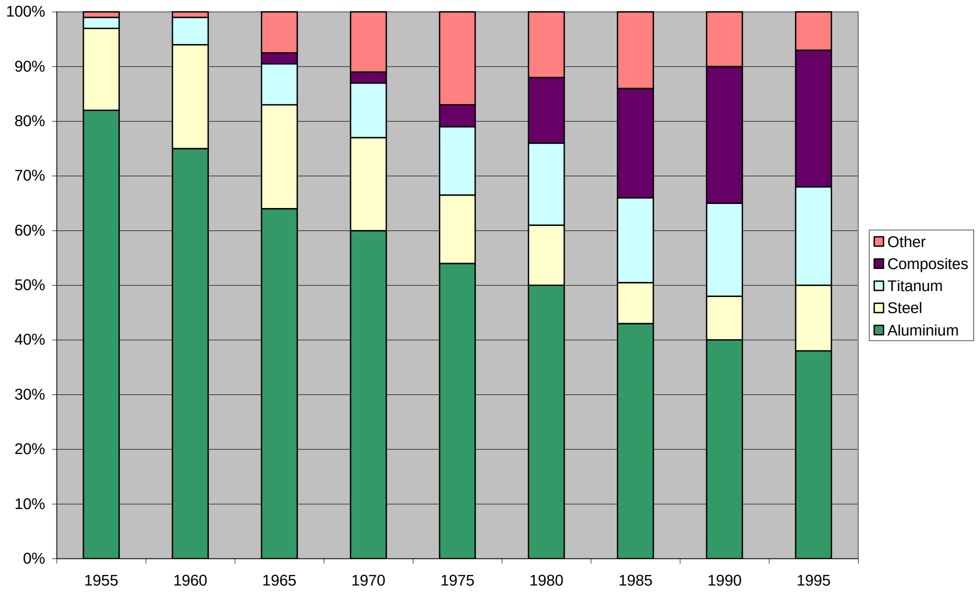


Figure 1.0-1 : Material Distribution of Fighter Aircraft by Structural Weight (average values)

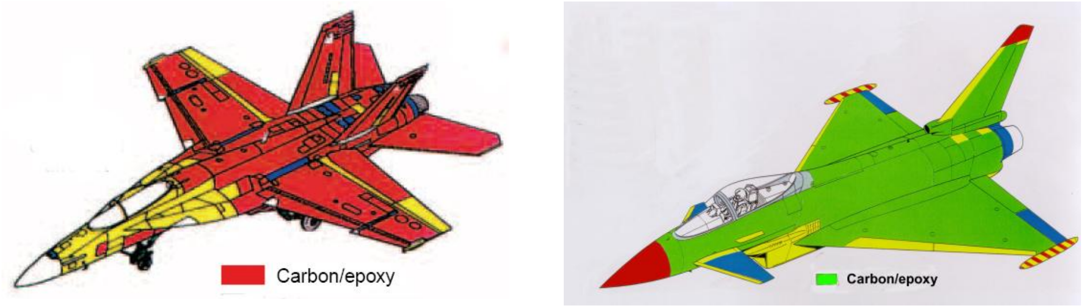


Figure 1-0-2: Outer Surface Material Usage of Modern Fighter Aircrafts

2.0 PEACE TIME QUALIFICATION AND CERTIFICATION

2.1 General

Certification and qualification of aircraft structures follow established processes to ensure adequate safety on aircraft level in the operational environment. Within this context the proof of continued structural integrity of the aircraft structure is an essential element and requires contribution of a variety of engineering disciplines such as structures, avionics and mission systems, flight mechanics, safety, maintenance, test, usage monitoring etc., Fig. 2.1-1

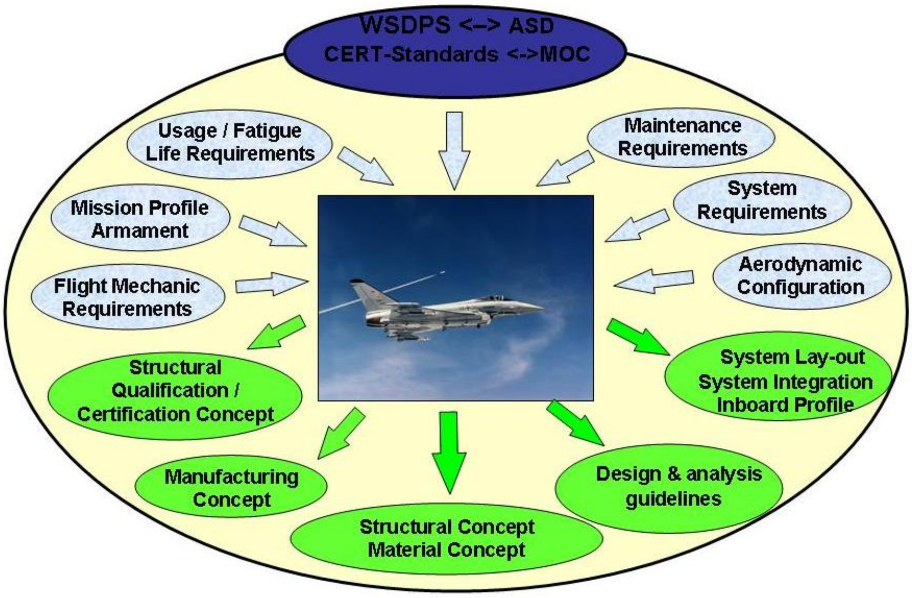


Figure 2.1-1 Aircraft Structures Qualification and Certification Disciplines

The qualification of an aircraft (or part of an aircraft) constitutes the process of verifying that a specific aircraft configuration complies with a specified set of requirements, taking into account its intended operational use.

Definition:

- Certification : Verifying compliance with applicable airworthiness requirements
- Qualification: Verifying compliance with contractual performance and functional requirements

Each operational aircraft is legally required to have a valid Certificate of Airworthiness. This certificate is issued by the Military Aviation Authority (MAA) on basis of conformity with the type design. The airworthiness certification aims at demonstrating "fitness for flight" of the type design and is formally acknowledged by a Military Type Certificate, issued by the MAA and kept under the responsibility of the Defence Materiel Organisation (DMO).

The Qualification Process basically conducted in accordance with the following steps:

- Qualification Basis definition: the (modified) configuration, its qualification status and the applicable requirements are defined in a Qualification Plan.

- Means of Compliance (MoC) definition: the verification methods that will be used and the activities that will be performed to demonstrate compliance with each requirement are defined in a Compliance Plan.
- Compliance Demonstration: the experimental and analytical verification activities are performed and documented in Test Reports and Verification Reports.
- Compliance Check: A final check is performed to verify that for each requirement all verification activities have successfully been performed and/or adequate follow-up actions have been defined. This check, together with a summary of the overall process and a recommendation for type certification, is documented in the Qualification Substantiation Report. /1/

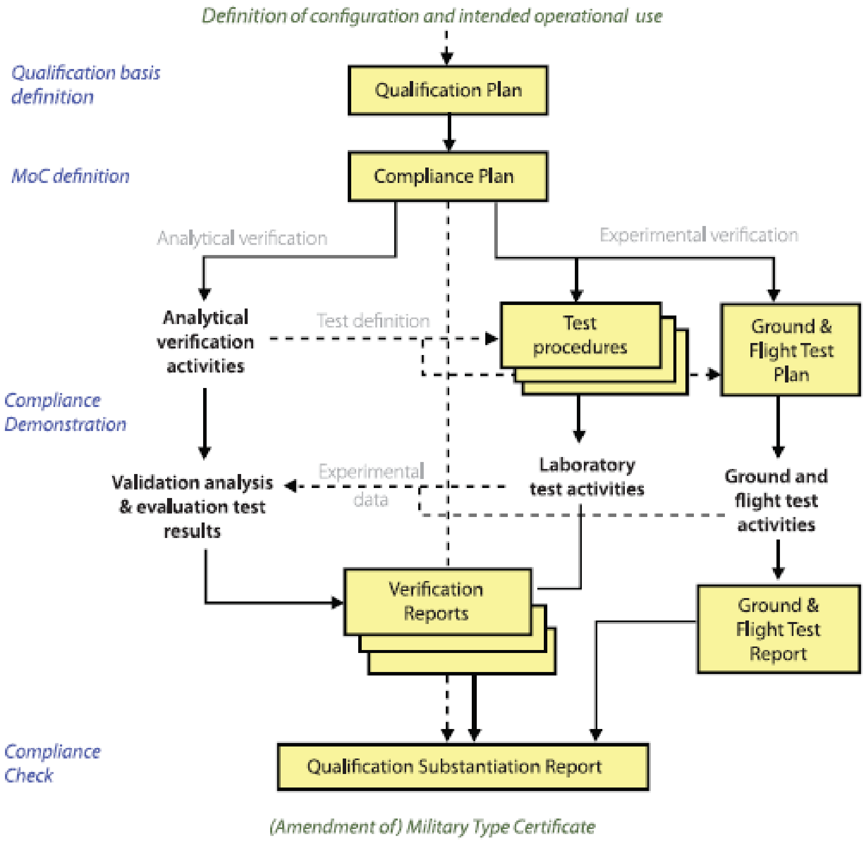


Fig. 2.1-2 Flowchart of Military Aircraft Qualification /1/

Other than in the civil world, certification standards and the associated acceptance standards are in most cases a national standard, sometimes vary from one service to another within a country and also reflect specific program / project needs for a balanced airvehicle design during development, production and in-service phases.

Structural design criteria are established following these national standards / guidelines, i.e. Mil-A-8860 series or DEF-STAN 970 and apply equally to different materials and design concepts used. In multinational developments programs these standards must be harmonized between nat. authorities and user communities. Compliance with these requirements is traced throughout the development program, the certification / qualification test phase , the introduction into service phase up to the force management tasks of operational fleets.

2.2 Qualification and Certification of Military Aircraft Structures

Comparable to civil development programs, design aspects of structures must also include operational performance requirements, such features like inspectability, repairability and replaceability. These aspects play a major role in selecting materials, design principles and internal load / stress levels and interfaces between structural groups. As an example, the maturity level of high strength / modulus composite design and service experience has long precluded the application of this material in fuselage bulkheads, a high loaded primary structure which is usually buried in the vehicle and is difficult to repair or replace, the same for wing skins bonded to inner structure, although it is obvious that static strength of the skins themselves are far more sensitive to bolted than to bonded joints.

Analysis alone is generally not considered adequate for substantiation of advanced structural designs, certification requirements most often call for : "verification by test, supported by analysis", therefore , the "building-block approach" to design development testing is used in concert with analysis, Fig. 2.2-1. This approach is often considered essential to the qualification/certification especially for composite structures due to the sensitivity of composites to out-of-plane loads, the multiplicity of composite failure modes and the lack of standard analytical methods.

Demonstrations of the requirements is shown via the "Building Block approach", a series of tests at increasing level of complexity, depending on the level of new technologies / design features introduced into the structure.

If new materials are used, small coupon size elements are tested with some "critical design features" (i.e. holes in composites, weldings in metals) already introduced.

The next level would introduce more complex loading and possible interaction of internal states of stress in a subcomponent; these component testing of (new) detail design features under environmental conditions representing the complete range of in-service conditions to identify possible shift in failure mechanism and sensitivity of different loading scenarios. They should also be used to substantiate durability / fatigue behaviour and verify analytical methodologies and predictions as a risk reduction element in the development program.

This is crucial especially for the new composite designs with their sensitivity to out of plane loads and multiplicity of failure modes.

Depending on the criticality of the subcomponent and the combination of loads and environments to be covered , the effort of subcomponent testing can be substantial.

Large scale elements, such as box beams allow more complex build up structural failure demonstration (i.e. combined strength / stability mechanism, or 2-dimensional skin loads including internal pressures. Design requirements must also include the unavoidable performance / strength degradation of materials and design elements from the in-service environment , i.e. temperatures, moisture pick up of composites, barely visible damages from maintenance operations or simply aging effects of metals, but also dedicated levels of discrete damage and repair Similar for metal structures, other building-block tests determine truncation approaches for fatigue spectra and compensation for fatigue scatter at the full-scale level. These test elements are often suitable candidates for damage level tolerance and repair evaluation.

The full scale test articles provide the background for envelope expansion through test flights (validating primarily the external loads and dynamic behaviour of the A/C) and determine the durability limits for operational usage.

The building block approach is shown schematically in Figure 2.2.-1

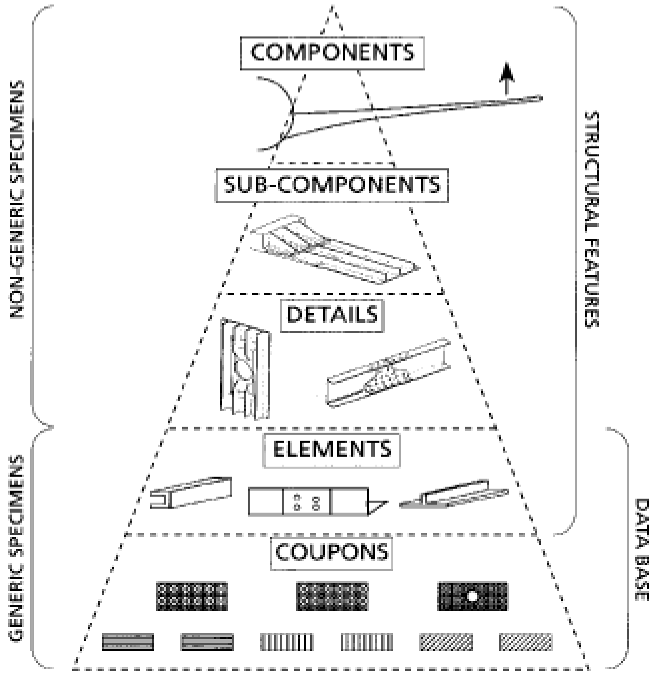


Figure 2.2-1 The Pyramid of Test Specimen in a "Building Block Approach" /2/

While some of these tests are certification related others are to be agreed between customers and design authorities, for example Fig. 2.2-2 shows results of a qualification program for composite skins with a 2 inch diameter repaired hole and the associated loss of static strength in tension for various temperatures and composite layups. The high strength / stiffness laminates (44/44/12), normally used for longerons and load introduction areas, suffer significantly from this repaired damage, especially at elevated temperatures, therefore the requirement to tolerate this damage in this area leads to a more "robust" and damage tolerable structure, but also requires reduced design allowables and therefore increases structural weight, therefore careful balance of these contradictive requirements is needed.

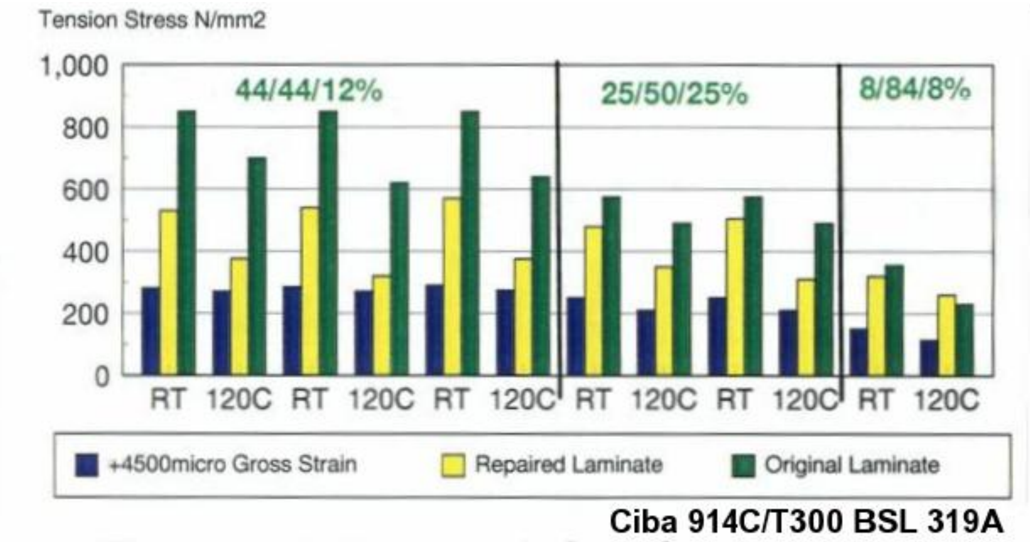


Fig. 2.2-2 Depot-level repair of 2" hole in high strength composite skins

3.0 REPAIR OF AIRCRAFT STRUCTURE, PEACETIME OPERATIONS VERSUS ABDR

The task of repair begins only after the extent of the damage has been established by cognizant personnel using inspection methods and damage assessment. The repair has the objective of restoring the damaged structure to a required capability in terms of strength, stiffness, functional performance, safety and service life. Ideally, the repair will return the structure to its original capability and appearance, often called "blueprint strength". To start the repair process the structural makeup of the component must be known and the appropriate design criteria should be selected, typical structural repair design criteria are:

- Part stiffness
- Static strength and stability
- Durability
- Damage Tolerance
- Related aircraft systems
    - Fuel system (Integrated fuel tanks)
    - Lightning Protection System
- Aerodynamic smoothness
- Weight and balance
- Operating temperatures
- Surrounding structure

The continuity in load transfer is re-established in a damaged part by attaching new material through bolting or bonding, thus bridging the gap or reinforcing the weakened portion. The repair is in reality a joint where a load is transferred from the parent material into and out of the patch. /2/

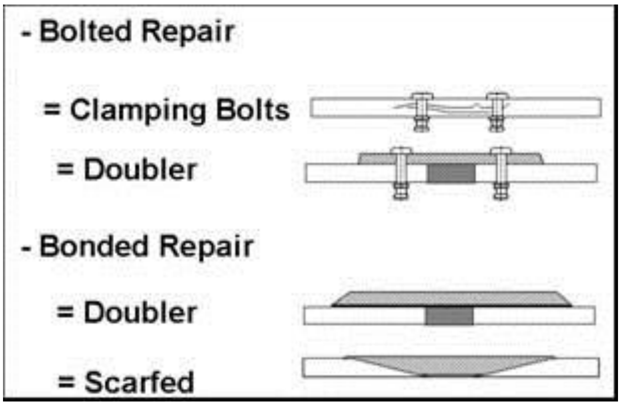


Figure 3.0-1 Principle Repair Methods

Only some of the shown repair methods (Fig. 3.0-1) are applicable in ABDR scenarios, because of time restrictions, special equipment and/or special trained personnel required. i.e. scarfed repairs for composite materials are not used for ABDR, although they can restore a component to its full design strength without unacceptable change in stiffness

3.1 STRUCTURAL DESIGN CONCEPTS FOR BONDED AND BOLTED JOINTS

The overall task for bolted and bonded joints in aircraft structures are identical: Permanently attaching two load carrying structures up to a defined load-level over a defined usage period (from one single flight to the entire remaining life of the aircraft). Repair design criteria, part configuration, and the logistic requirements will dictate whether the repair should be bolted or bonded (see Figure 3.0-1). Some of the main drivers that determine the type of repair are listed in Figure 3.1-1.

Condition	Bolting	Bonding
Lightly Loaded, Thin (<0.10 in. [2.5 mm])		X
Highly Loaded, Thick (>0.10 in.[2.5 mm])	X	X
High Peeling Stresses	X	
Honeycomb Structure		X
Dry and Clean Adherend Surfaces	X	X
Wet and/or Contaminated Adherend Surfaces	X	
Sealing Required	X	X
Disassembly Required	X	
Restore Unnotched Strength		X

Table3.1-1 Drivers for Bolted or Bonded Repairs /2/

However, the engineering properties, manufacturing processes and qualification efforts of both methods are different and have led to distinct applications for both types of joints, i.e.:

- Bonded joints are up to a magnitude stiffer in shear than bolted joints.
- Mechanical interface versus chemical reacted joint material.
- Good combined shear and cross-ply tension behaviour of bolted joints compared to bonds. Load transfer along joints are non-uniform for both types (except scarf joints in isotropic materials).
- Bolted joints show redundant loadpathes, where bonds act as "Single Fastener Systems".
- Bolted joints are fatigue sensitive in metal adherents, while properly designed bonds show almost unlimited mechanical life.
- Quality assurance procedures are based on visual, mechanical checks for bolts, whereas chemical processes for adhesives and surfaces are far more complex to control.
- Bonded joints can act as sealings between structural elements.

The above list is not complete, but gives an indication why bonded joints historically have been applied to aircrafts mainly to thin structures and honeycomb panels with low load transfer and conservative design approaches in a production environment with good process control.

Unlike metal fatigue design concepts of slow and controlled crack-grow under cyclic loading, defects in bonded joints will either never grow under mechanical load (providing adhesion of the glue to the adherent is existing) or very rapidly with no predictable life remaining.

Therefore high loaded load-introductions in A/C structures are still the dominant area for "close tolerance bolted joints", where read across of quantitative joint strength from coupon testing is easy and production control is limited to material, standard parts and geometric checks.

Still today no satisfactory technique is available for the detection of poor adhesion, so these possible defects must be eliminated by checking the adherents prior to bonding and careful process control. Time elaborating ultrasonic-, sonic vibration and X-Ray techniques are the methods most commonly used for the detection of physical disbonds and porosity. The most appropriate method depend on the type of structure , test environment and on the minimum size of defect which must be detected. In composite joints, the minimum detectable defect size is often larger than in metal to metal joints.

In summary, the application of primary bonded joints is always linked to extensive engineering and manufacturing development phases for a special component and qualification/ certification programs within the aircraft development phase.

In principle the qualification of bolted or bonded joints and the certification of structures including highly loaded joints follow the "Building Block Approach" as depicted in chapter 2.2. Figure 3.1-2 shows examples of repair qualification / certification level.

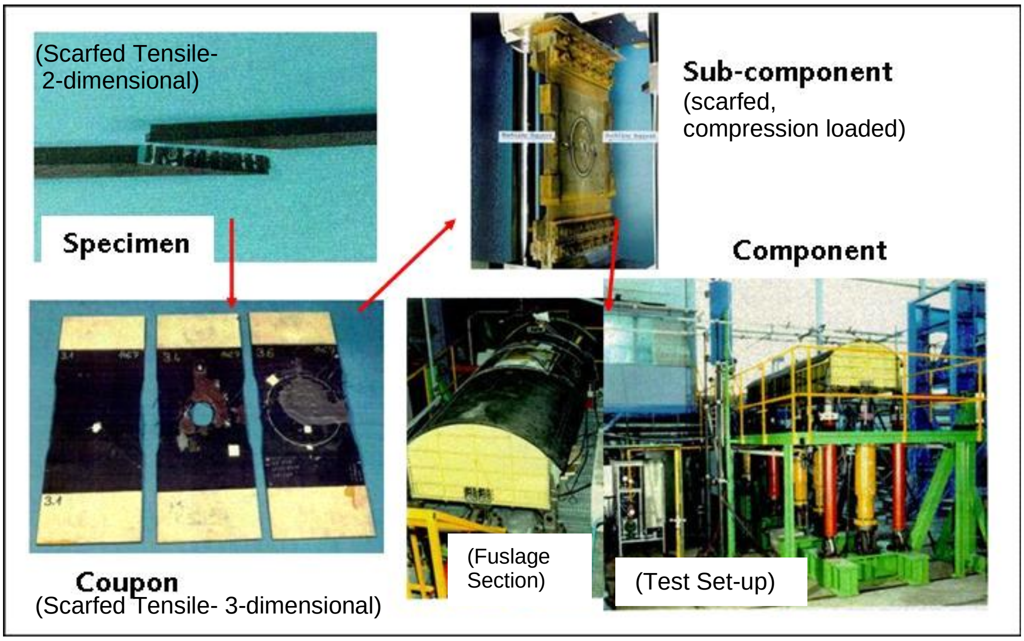


Figure 3.1-2 Repair Tests for Qualification

4.0 AIRCRAFT BATTLE DAMAGE REPAIR QUALIFICATION

Aircraft Battle Damage Repair (ABDR) is the topic of rapid identification, assessment and recovery of battle-type damage to an aircraft, aimed at restoring a level of flight and mission capability as required to fulfil the immediate operational requirements of the operator at a time of conflict. Airframe service life and durability considerations have reduced importance. The functionality of certain systems and/or their associated components may not always be essential when the requirements of the next operational mission(s) are considered.

Battle damage will vary considerably in size, shape, extent, coverage and effect on structures. The number of combinations that can affect an aircrafts structural integrity is virtually infinite, therefore any qualification of ABDR is based on analysis and testing of:

- Representative repair designs
- Typical structural elements
- Anticipated damage sizes
- Representative loading conditions and environments

4.1 ABDR process and elements for qualification

Typically, the primary aim of the ABDR process is to restore the full operational capability of a damaged aircraft in a short time. This includes restoring the structure to the required design strength and systems to their full functionality. This will enable the aircraft to carry out a full operational mission. Although any structural restoration will not necessarily recover, nor guarantee, the remaining service life of the airframe.

When it is not possible to achieve the primary aim, the secondary aim is to make the best possible recovery in the time available, to meet the short-term requirements of the operator without imposing unacceptable limitations on the repaired aircraft. Ideally, this should restore as much functionality as possible back to full capability. However, it may only be sufficient to enable one flight with very limited functionality/capability.

Fig 4.1-1 shows typical elements of the ABDR process where qualification evidence / information from A/C specific and general ABDR-documentation is required.

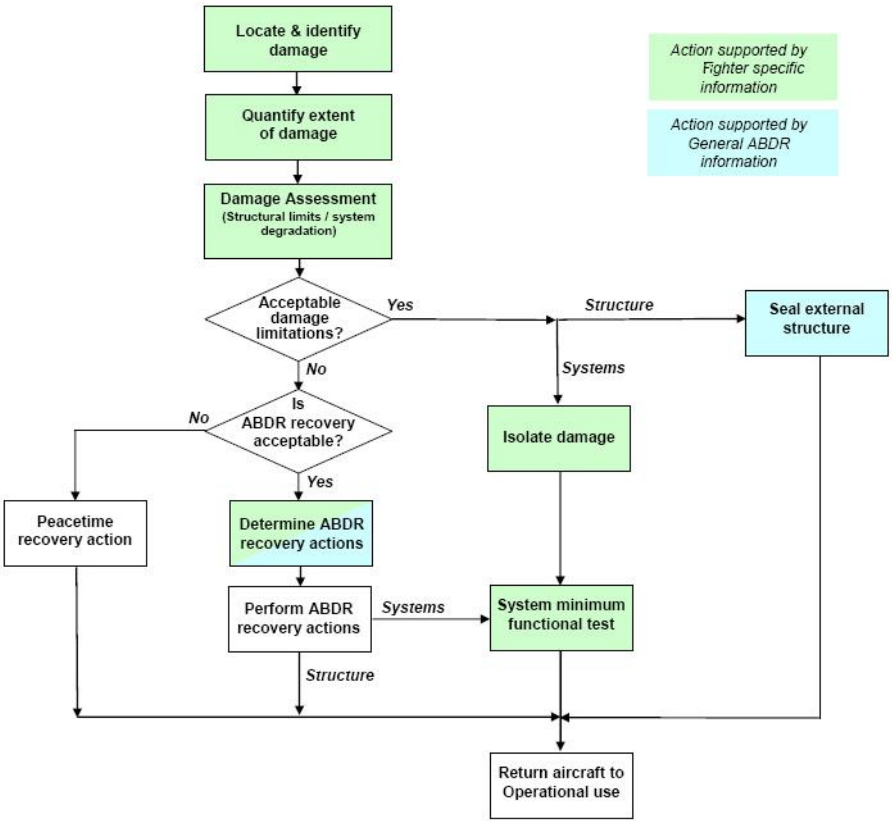


Figure 4.1-1 Typical elements of the ABDR process

4.2 Damage assessment and repair categorisation

Each item of ABDR is determined as being of a particular damage repair category. These categories are used to identify 'at a glance' structure to which repairs are not permitted, or alternatively, the minimum extent required of any ABDR-type repair. The vast majority of items are anticipated to fall into Category 2 (Fig 4.2-1 and Fig 4.2-2).

Category 1	Structure to which ABDR-type repairs are NOT permitted (i.e. item to be replaced)
Category 2	Structure to which ABDR-type repairs are permitted
Category 3	Structure which is not structurally significant but which can be ABDR repaired for aerodynamic reasons.

Figure 4.2-1 Structural Damage Repair categories

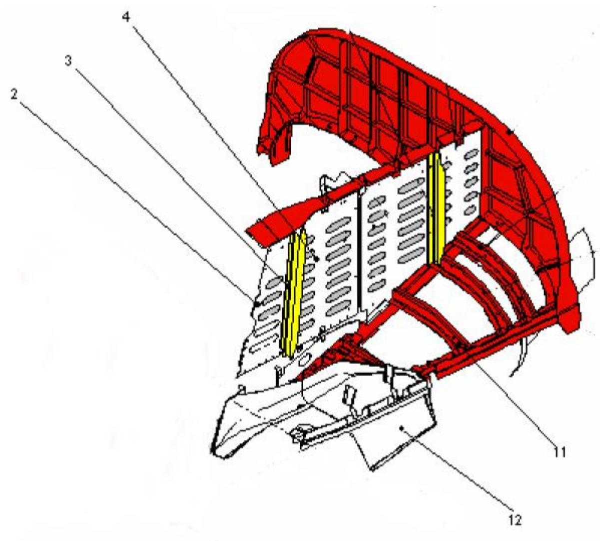


Figure 4.2-2 Example for structural categorisation (Cat 1: red; Cat 2: yellow)

4.3 Remaining Structural Capability (Permissible Damage)

The types of structure, the design principles and materials used should be considered. Primary structures, such as beams, frames, longerons, and fittings, are essential to structural integrity / safety of flight, since the airframe depends on the distribution of loads through the individual structural elements. When combat damage reduces the strength, stiffness, or stability of these elements, a decision on suitable repair methods must be made. This critical decision has to be based on a judgment of whether redistribution of the loads may degrade flight safety or adversely affect flying qualities.

- Structural Strength / Stability

  The relationship between damage severity and remaining structural capability is defined (e.g. by graphs and/or data tables) - see Figure 4.3-1 - for component damage size related to vertical load factor Nz. For clarification additional qualitative text is included. Where more than one mission parameter has been affected, separate tables/graphs are provided for each.

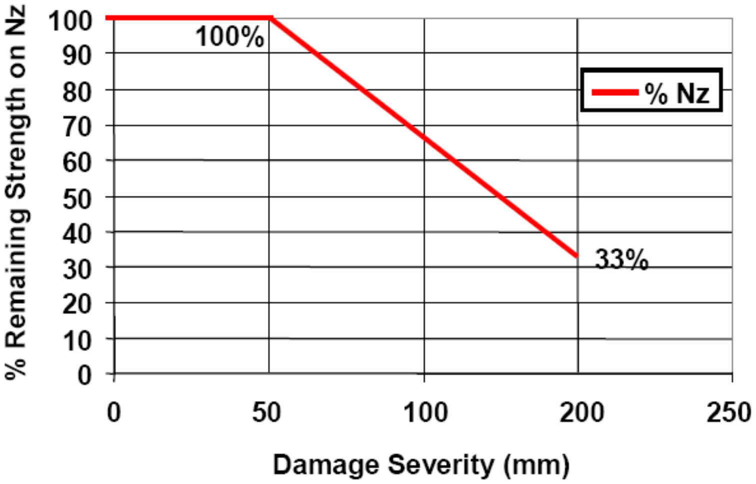


Figure 4.3-1 Illustrative example relating damage severity to remaining structural capability

- Structural Function

  The structural function(s) of an item considered must include purpose and function of the part relative to the flight parameters of the vehicle, reflecting its structural property (eg. strength, stiffness, etc.), However, other non-structural functions of significance should also be identified where appropriate (e.g. forming a fuel tank boundary). Functions should be expressed in terms of relevant loading actions (e.g. wing bending, fuselage shear, etc.) with links to 'mission parameters'. Mission parameters are those main aspects of structural capability which may be affected in operating the vehicle. Typical examples are :

  - Nz – symetric pull up / push over
  - Roll / yaw rate
  - Airspeed / Mach-No. / flutter critical components like control surfaces
  - Landing / braking / arrest parameters/
  - Cockpit pressurisation / altitude envelope
  - Store carriage / release envelope
  - In-flight refueling
  - Airbrake operation

4.4 Examples of Qualification Elements for ABDR

The following examples are provided to illustrate repair qualification items on different levels of complexity. A typical damage scenario for a stiffened monolithic skin of moderate curvature is shown in Fig. 4.4-1, in this illustration with shell damage to the skin only, requiring repair of the in-plane loading directions of the skin and possible sealing of the compartment.

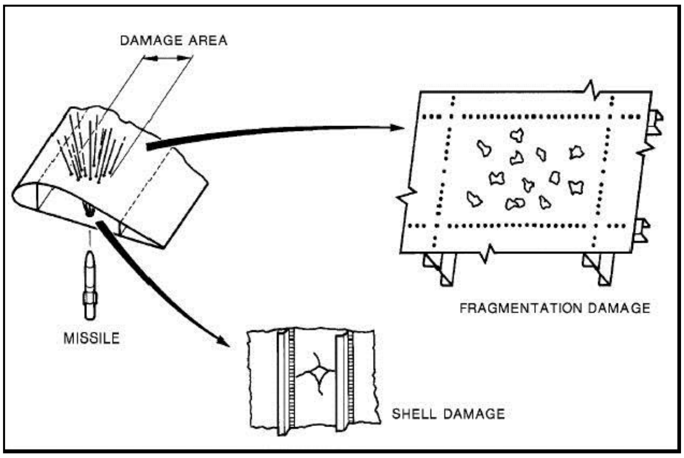
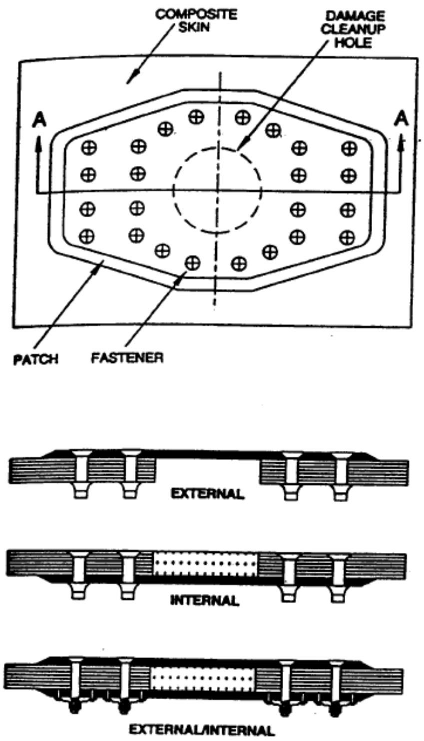


Figure 4.4-1 Typical ABD in monolithic skin structures

Repair qualification can be obtained by analysis and / or testing of bolted patch repair doublers and sealing the compartment.



/2/

Figure 4.4.-2 Typical ABDR principle for monolithic skins

Qualification elements that can be derived from these tests are:

- Manufacturing quality of bolted joints (if performed under ABDR environment)
- Functionality of the sealing (if performed under ABDR environment)
- Load transfer capability for various inplane loading combinations

- Sensitivity for variations in bolt pattern (i.e. needed due to substructure limitations)
- Lightning strike capability of repair (if required for ABDR scenario).

A qualification element test for a more complex structure and damage scenario is shown in Fig 4.4-3. Here the damage is assumed to extend into the cocured or cobonded stiffener, which provided both longitudinal strength and buckling stability to the overall panel. Therefore a more sophisticated repair method using aluminium sheet metal repair elements of various thicknesses was selected to achieve 100 % of original design strength and a close match of stability properties for the stiffener, like area centre of gravity (c.g.) together with a substantial resistance to fatigue loading after static preload. A min. additional weight requirement was added to qualify this method for repair of weight sensitive structures in dynamic environments (i.e. flutter of control surfaces).

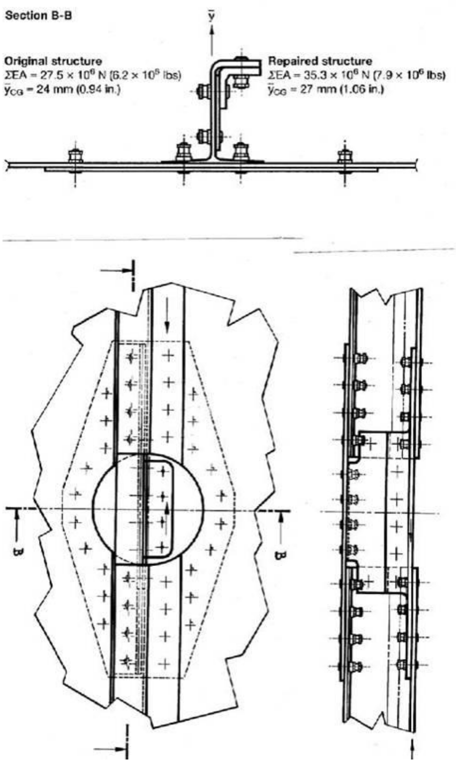


Figure 4.4-3 Bolted repair scheme for stiffened skin of non- or pressurized compartments

A comparison of the main properties of original structure and ABD-Repair are shown in Fig. 4.4-4.
A total of eight individual structural elements were tested in pure compression and shear with static and fatigue loading conditions. The max. fatigue loading exceeded for both loading conditions the buckling limit of the panel, introducing secondary loadings into the repair patches in the post buckling regime. All test specimen failed at gross panel strains above the ultimate design limit level.

Mechanical property	Original Structure	ABDR-Structure
Total longitudinal stiffness	27,5 x 10^6 N	35,3 X 10^6 N
Aera-C.G*., distance from skin	24 mm	27 mm
* Center of Gravity		

Fig. 4.4-4 Comparison of the main properties of original structure and ABD-Repair

Typical qualification elements derived from these tests are:

- Damage evaluation limits (physical access restricted)
- Accessibility for repair from single side (i.e. into fuel tanks)
- Manufacturing quality of bolted joints (if performed under ABDR environment)
- Functional quality of tank sealing (if performed under ABDR environment)
- Load transfer capability for various inplane loading combinations and internal pressure

The following example illustrates the qualification for a highly loaded, complex contoured integrally stiffened panel with single side access. The task was performed on a component, where the failure load and location was identified through a static test to failure under hot-wet conditions.

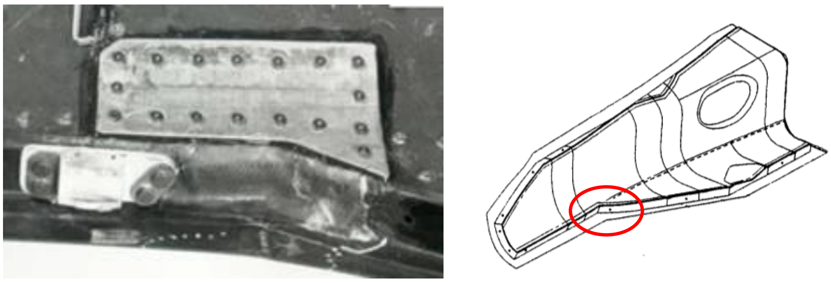


Figure 4.4-5 Example for ABDR in composite structure (fullscale component test of MLG-Door)

The test failure was located in a complex geometric stinger joggle, cocured to the inner structure with single side access. Due to the high energy release at the moment of static failure, multiple delaminations and structural disintegration occurred in the vicinity of the damage origin. The ABD-Repair was performed by military repair teams with standard ABD-Equipment and no previous repair analysis performed using aluminium sheet metal and blind fasteners and wet lay-up laminate for sealing.

After completition of the repair, the component was tested again for the critical loadcase under environmental conditions and achieved ultimate design load level without local failures in the repair area.

Typical qualification elements that can be derived from these tests are:

- Damage evaluation limits (main load carrying stringer damage)
- Accessibility for repair from single side
- Manufacturing quality of bolted joints (performed under ABDR environment)
- Load transfer capability for complex in-plane and secondary loading effects in high loaded repair area
- Repair sensitivity to environmental conditions

5.0 ABDR INFORMATION ON REPAIR QUALIFICATION

ABDR information provide an expeditious means of combat damage assessment for deferment or repair. Basic repair information and general instructions and methods for the rapid repair of battle damage. This information is contained in the national **general** ABDR manuals which are prepared and published by the National Air Forces and are applicable to **all weapon systems** .

Weapon system **specific information** such as pre-calculated acceptable damage limits and system degradation information, special repair methods or materials should be based on the **qualification program.**

Typical materials used in modern air vehicles include aluminium, steel, titanium, magnesium, and composites. Since sheet stock and extruded materials that are not preformed are needed for most repairs, some of these materials can be worked and formed into airframe structures, such as brackets, ribs, bulkheads, extrusions, or even honeycomb-sandwich replacement structures. Fig. 5.0-1 shows a typ. substitution of original design and material by ABDR- elements .

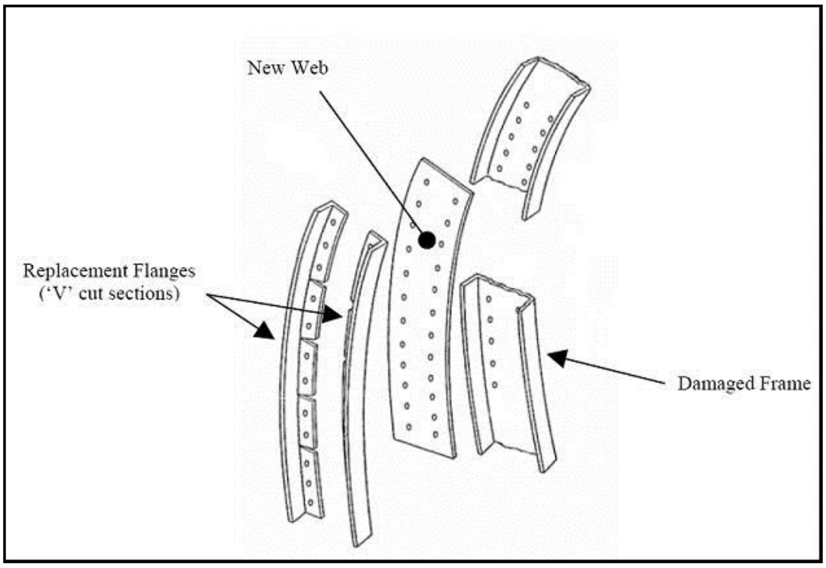


Figure. 5.0-1 Alternative or substitute repair materials matching original materials

6.0 SUMMARY

In peacetime, the main aim of repair is the recovery of an aircraft to a standard that recovers its design capability over its remaining full service life. This is achieved by the restoration of the structure to meet the requirements of the original design standard. Additionally, the aircraft systems are normally restored to full functionality. In wartime however, service life, and consequently durability considerations, assume a lesser degree of importance, and the functionality of certain systems and/or its parts, is not always essential when the requirements of a particular operational mission are considered. Thus in wartime, the repair aims can be reduced without affecting the operational capability of an aircraft, resulting in a reduced time being spent on repair work and an increase in aircraft availability.

The ABDR concept in general is based on the assumption that actual aircraft battle damage in all its possible combinations will produce effects that are not predictable. Thus, since the damage details are not known in advance, the required repair solution cannot be predicted in detail. Consequently, the detailed procedures normally required for standard repair cannot be prepared beforehand. For this reason a 'flexible repair' policy is applied which relies on the judgement of an experienced aircraft battle damage assessor, supported by WS specific ABDR information and general instructions for the repair of battle damage, to assess whether or not repair is necessary and, if required, to formulate an appropriate creative repair scheme to allow for an expedient repair solution.

Certification of ABDR is therefore not possible and must be substituted by qualification of "typical" damage scenarios and repair processes, adapted to the structural design details and supported by weapon system qualification (and certification data) coming from

- Ballistic survivability analysis and tests
- "Building Block Approach" test data
- Damage tolerance design approaches in the pristine structure
- Repair qualification test data

This data are transferred to the ABDR assessment information based on:

- Damage tolerance approach
- Analysis
- Read across
- Engineering judgement

ABDAR is a temporary alternative to a full standard repair or repair by replacement, which are considered to be peacetime activities. In case ABD-Repairs are kept operational beyond the original anticipated (restrictive) usage time, they must be closely monitored and replaced by peacetime repair as soon as practicable.

[1] National Aerospace Laboratory NLR "Qualification of Military Aircraft"

[2] MIL-HDBK 17 "Composite Materials Handbook"